Strategies to reduce greenhouse gas emissions from particle detectors at CERN

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CERN | EP-DT Detector Technologies



Outline

Greenhouse gases for particle detectors at CERN

Main strategies for GHG reduction

- Gas recirculation
- Gas recovery
- Further R&D studies

Conclusions

Greenhouse gases for gaseous detectors at CERN

Greenhouse gases

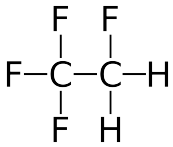
The strength of a GHG is defined by its Global Warming Potential **GWP** (GWP_{CO2} = 1)

GHGs are often required in gaseous detectors

Fluorinated gases account for the **biggest emissions** at CERN

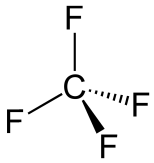
Most of F- gases were used before their environmental impact was understood

One gas can have multiple roles in gaseous detectors (in particular CF4)



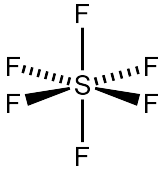
C2H2F4/R-134a (GWP = 1430)

Used in **RPCs** for primary ionization and charge multiplication



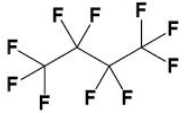
CF4 (GWP = 7390)

Used in **RICHs** (optical properties), **Wire** chambers (anti-polymerization) and **MPGDs** (time resolution)



SF6 (GWP = 22800)

Used mainly in **RPCs** as electron quencher



C4F10 (GWP = 8860)

Used in **RICH** for optical properties

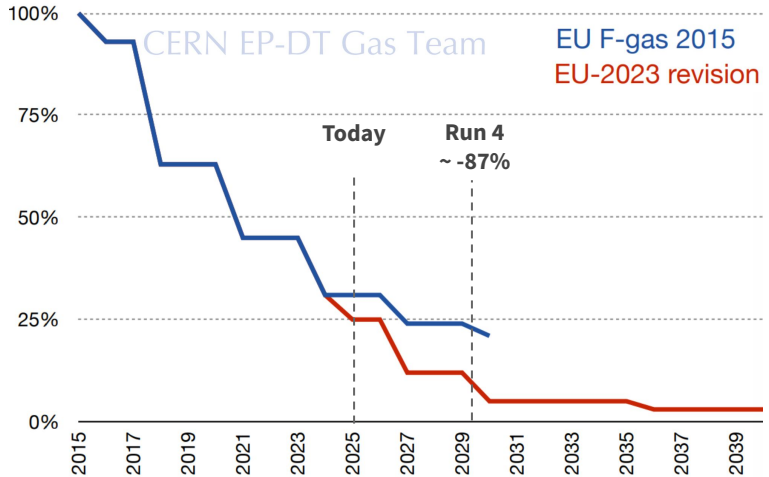
F- gas regulations

EU regulation on F- gases

Aim at **limiting** and preventing F- gases use

F- gas consumptions should be reduced:

- Environment
- Price
- Availability



Revised regulations + PFAS

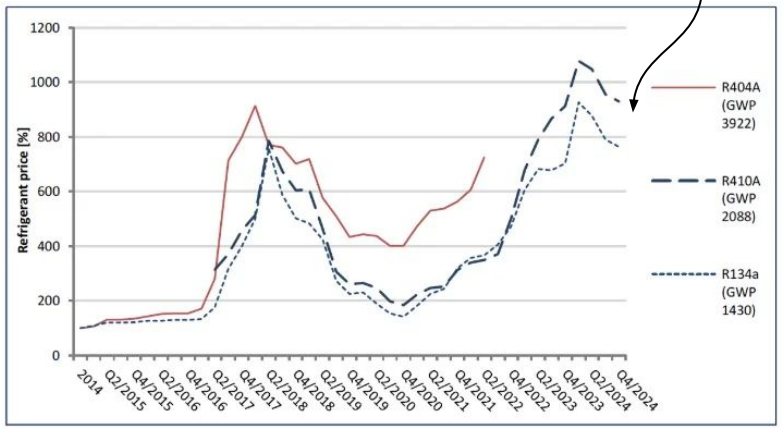
PFAS: New EU regulation that includes F- gases

- EU Chemical Agency proposing to ban most of them
- Not clear yet if low-GWP HFOs are included

Revised regulations:

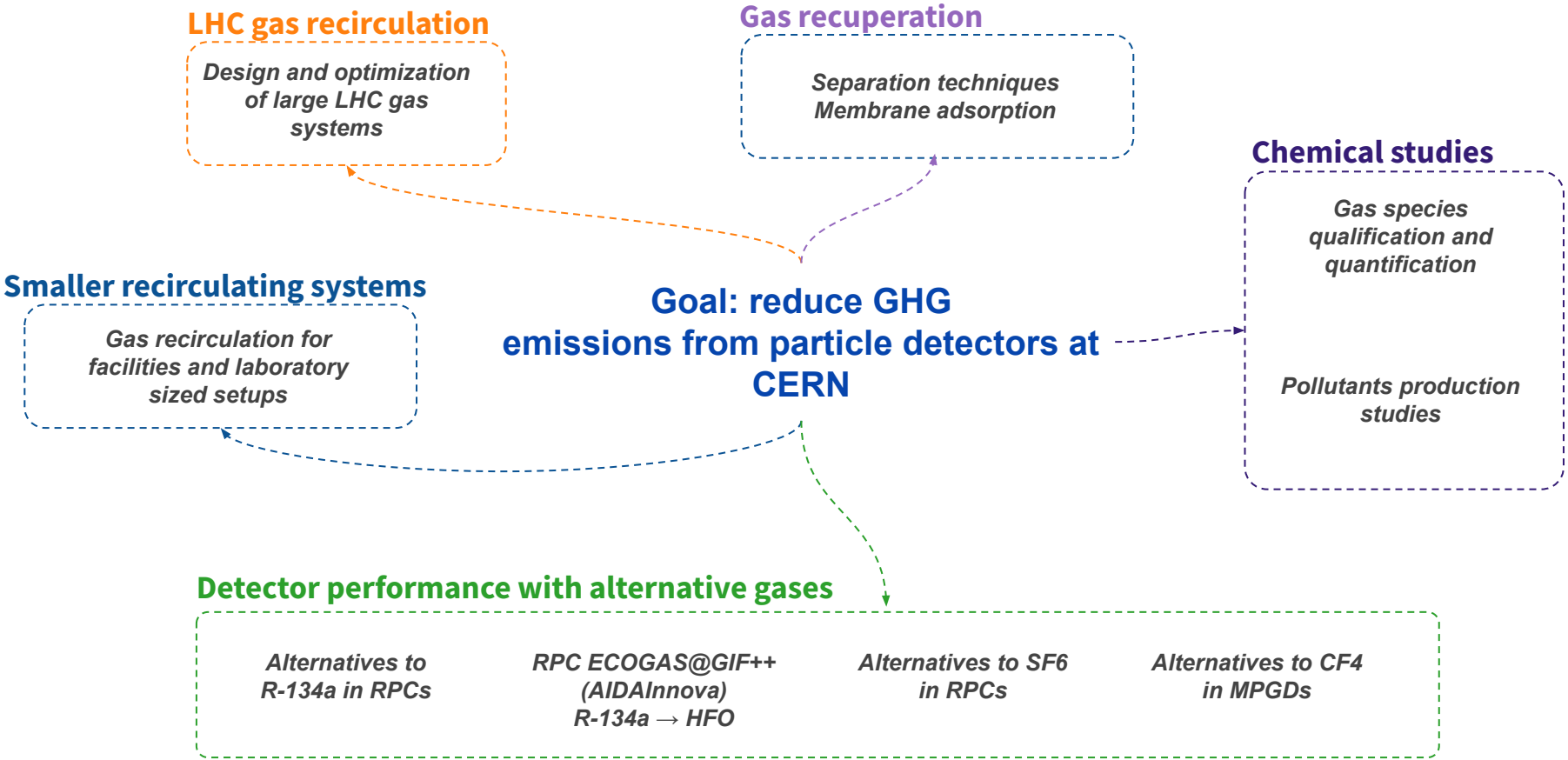
- EU F- gases
- Montreal Protocol on HFC

R-134a price ~8 times higher



European report 2025

GHG reduction strategies overview

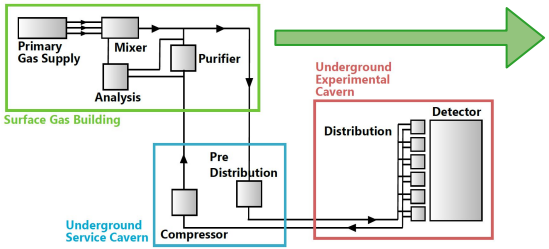


Gas recirculation

CERN Gas Systems

Most important approach to reduce GHG consumption

Gas recirculation modules



ATLAS RPC Gas Systems in surface gas building



Gas **recirculation** can be save gas up to 100%

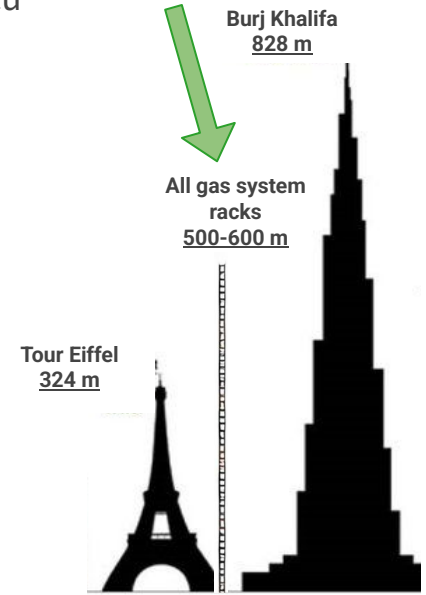
- Most gaseous detectors still require 10% fresh gas → max 80-90% recirculation

CERN LHC gas systems installations

- Modular design: 30+ installations ~150 standard modules
- ~hundreds of sensors per system
- ~few to hundreds of actuators per system
- ~2-3 km of pipes per system
- designed for large detector volumes: 1-100 m^3

Gas Systems performance

- Fine pressure regulation: better than 0.1 mbar
- Flow regulation accuracy: ~ ln/h
- >= 99% uptime efficiency (excluding external reason)
- Gas mixture quality: better than 0.1%
- Among the largest PLC control systems at CERN



Small and micro recirculating gas systems

Several facilities and laboratories using GHGs

The **sum** of contributions from **smaller facilities** is sometimes comparable with **LHC gas systems**

Laboratory-size, recirculating gas systems

- **Small** (~liters)
- **Compact and affordable** (~ kCHF)
- **Component validation** (LHC)

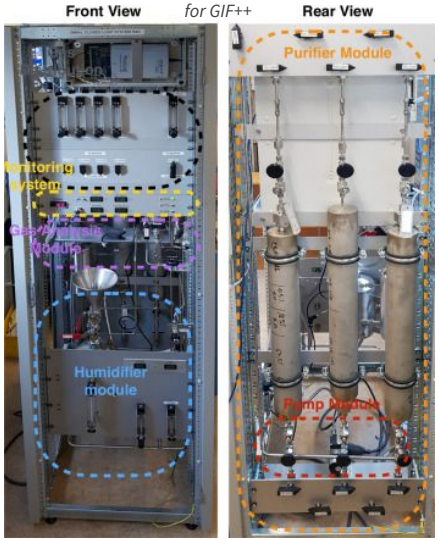
Micro-loop

- **Portable** gas system for laboratory setups
- **R&D** still **ongoing**: right component selection is the most difficult part

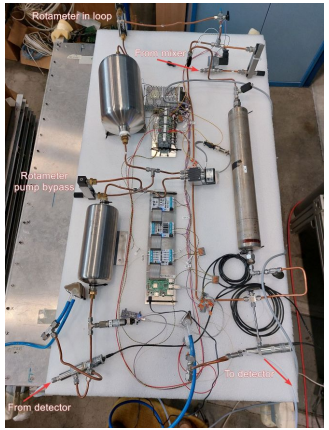
Challenges

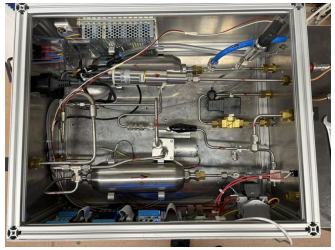
- **Standardize** a small system
- Affordable but reliable components (pump validation)

Small recirculating systems for GIF++

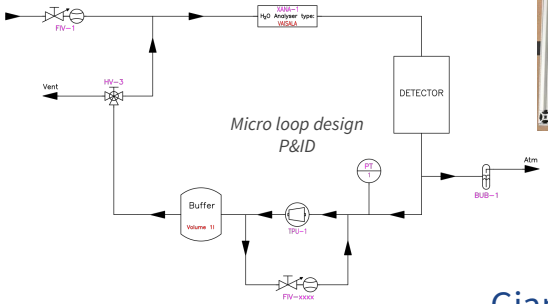


EEE R&D prototype





Micro loop design for Picosec detector



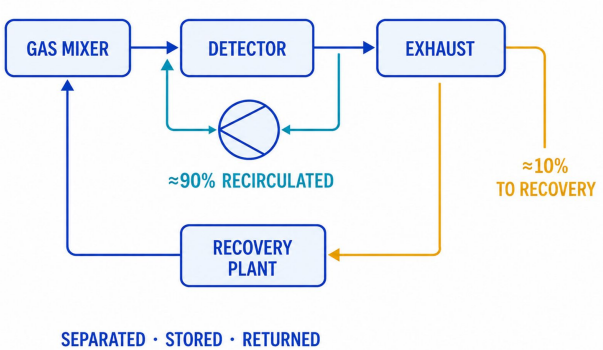
Micro loop design P&ID

Gas recuperation systems

Gas recuperation systems: overview

Motivations for recuperation systems

In most systems, **not all the gas can be recirculated** due to detector requirements ⇒ some gas needs to be exhausted



Working principle

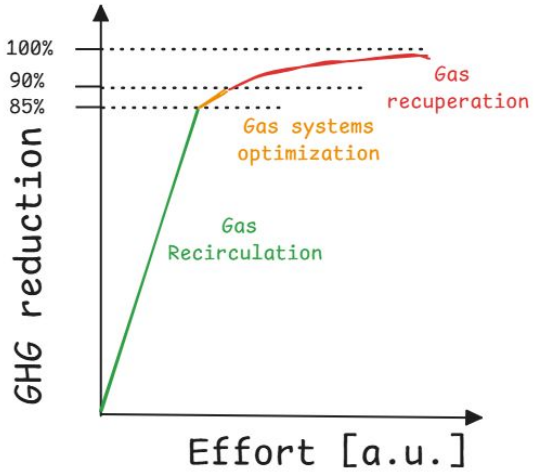
1. Gas mixture at the **exhaust** sent to the recuperation
2. One components of the gas mixture is **separated** from the other gas components of the mixture
3. Gas is **stored** into bottles and reused as a **fresh gas**

Pros and Cons

- Suitable for **large** LHC **installations** ⇒ ~m^3gas spares, kCHF saves
- Non standard and **complex** systems
- Each recuperation system **specifically designed** for a gas mixture and a gas system
- Dedicated **R&D**, **maintenance** and **operation** needed

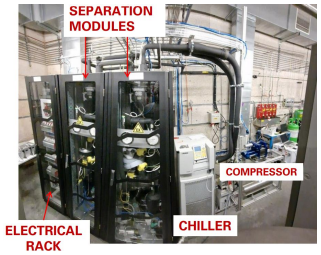
Gas recuperation systems allow to reduce GHG emissions

- About 60-85% of the exhausted gas can be recovered (theoretical + technology limits)



LHC recuperation systems

CMS RPC R-134a recuperation



CMS CSC CF4 recuperation

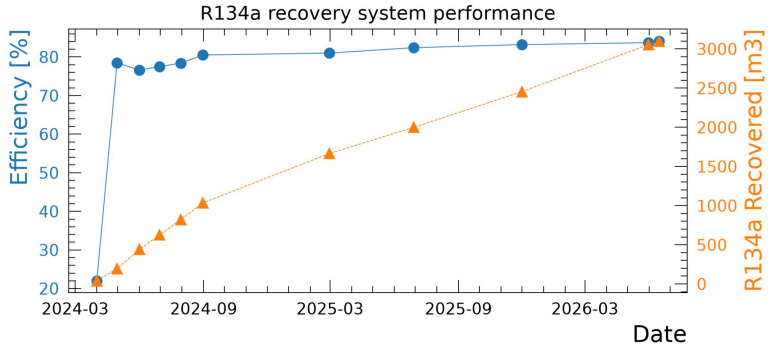


LHCb RICH1 C4F10



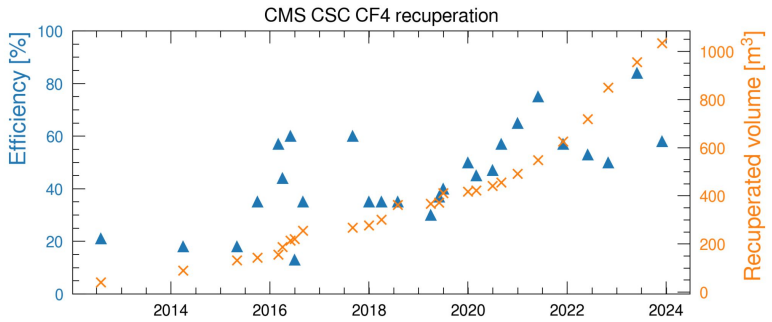
CMS RPC R-134a

- Operated in Run periods
- Recovers **R-134a** from **CMS RPC** gas mixture
- Complex separation technique due to **azeotrope** between R-134a and isobutane
- Efficiency up to **80%, ~99.5%** quality.
- **12 t/year** (24t needed) R-134a, **18 ktCO2e**, ~ **130 kCHF/year** saved



CMS CSC CF4

- Operated in Run periods
- Recovers **CF4** with **membranes** adsorption and pressure swing cycles
- **~60-70%** efficiency, **~90%** quality
- **1400 kg/year** (2200 kg needed), **10.5 ktCO2e** ~ **68 kCHF/year** saved



LHCb RICH2 CF4

- Operated only when changing mixture in the detector
- ~**70%** efficiency, ~**95%** quality

LHCb RICH1 C4F10

- Operated only during specific periods (cleaning, filling, emptying)
- New system built and being tested
- ~**80%** efficiency, ~**98%** quality

Recovering gas from detector exhaust

Idea: collect gas at the gas system for later treatment in a centralized system

ALICE MID pilot test

Compressor module at the exhaust

Use CO_2 to displace gas

Separate CO_2/R-134a at the exhaust with a membrane

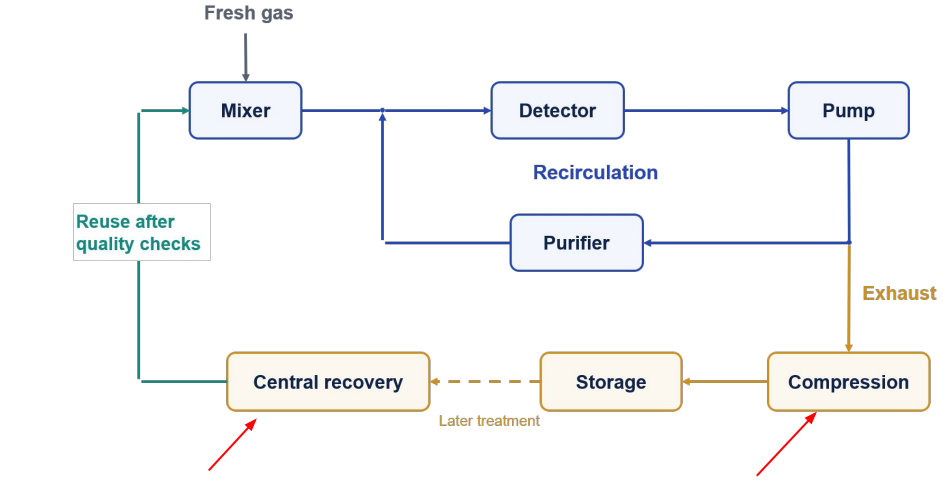
Compress and store the gas into a tank

Results

3.11 kg of R-134a recovered

85% efficiency (730/860 l R-134a)

85% purity (730/ 840 l total recovered gas)





R-134a distillation system



Gas compression module

R&D studies

Membrane separation technique studies

Objectives

Use membrane to separate fluorinated gases

EPFL collaboration

Studies on separation of SF6 from N2

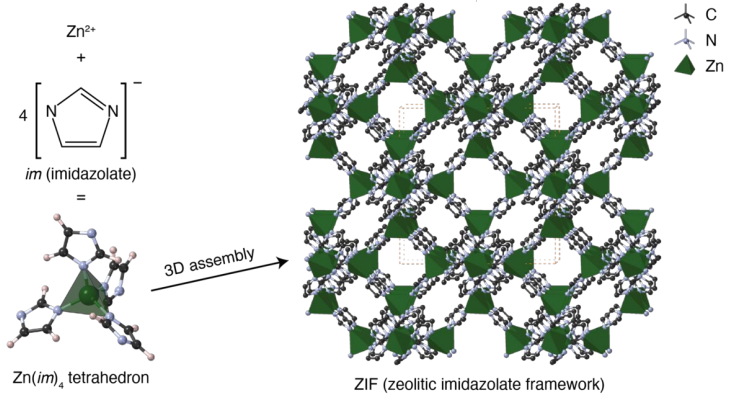
Phases:

1. Synthesis of highly specific material (ZIF-8) + layer tuning via secondary growth
2. SEM characterization and preliminary gas separation testing
3. Simulations and reiteration on material properties design

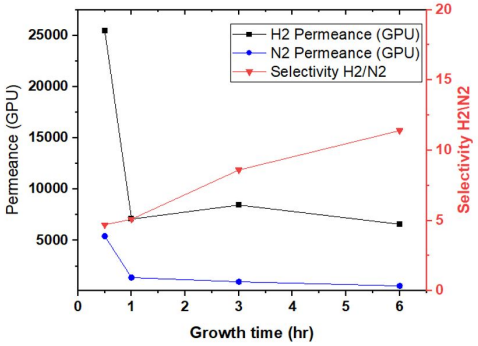
Preliminary results

N2/H2 selectivity > 10 with 3-6 h growth time → sieving behaviour of membrane

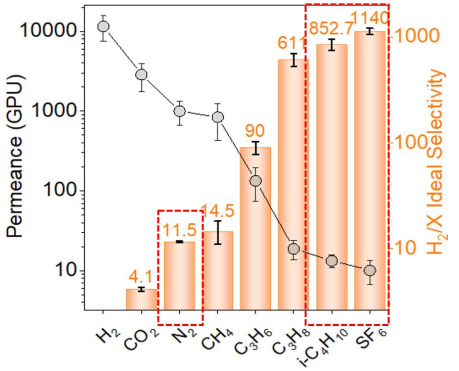
N2/SF6 selectivity ~ 100, enabling SF6 recovery via membranes



ZIF-8 secondary growth



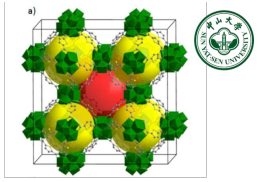
ZIF-8 performance



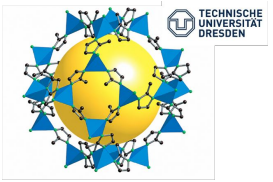
R-134a adsorption techniques

R&D lines

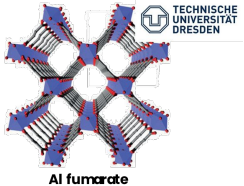
- **Removal** of R-134a accumulating from leaks in experimental caverns
  - During LHC Run period when the cavern is closed
- Enable **SF6 recovery** by **removing** residual **R-134a** traces from exhaust of R-134a recuperation system
- Recovery of R-134a from azeotropic mixture exhausted by recuperation system



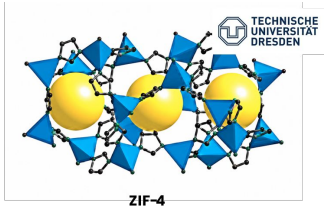
DUT-67
pore diameters 14.2 Å and 11.7 Å.



ZIF-8,
pore diameter 11.6 Å • Window 3.4 Å (flexible).



Al fumarate
pore size 5.7 Å × 6.0 Å.



ZIF-4
flexible pore diameter 2.04 Å.

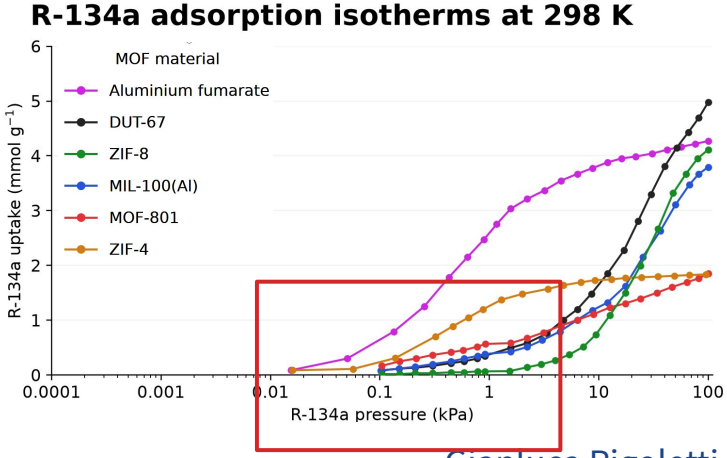
Studies on Metal Organic Frameworks (MOFs)

- Technology enabling designing specific structure to adsorb gases with high selectivity

Two regimes:

- R-134a in atmosphere at 10-100 ppms levels
- R-134a in exhaust gas at 70% levels

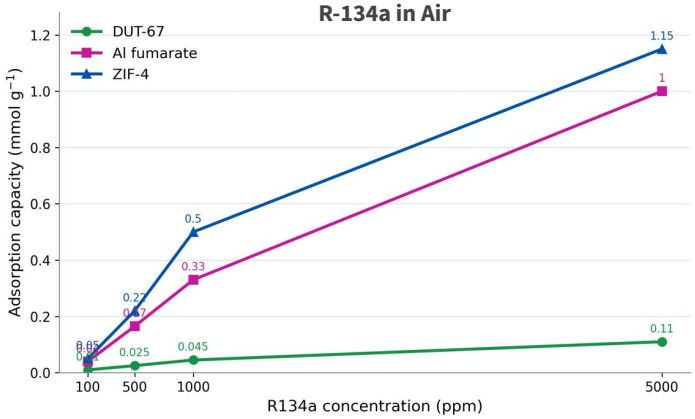
MOFs development → nobel prize 2025



R-134a adsorption techniques: preliminary results

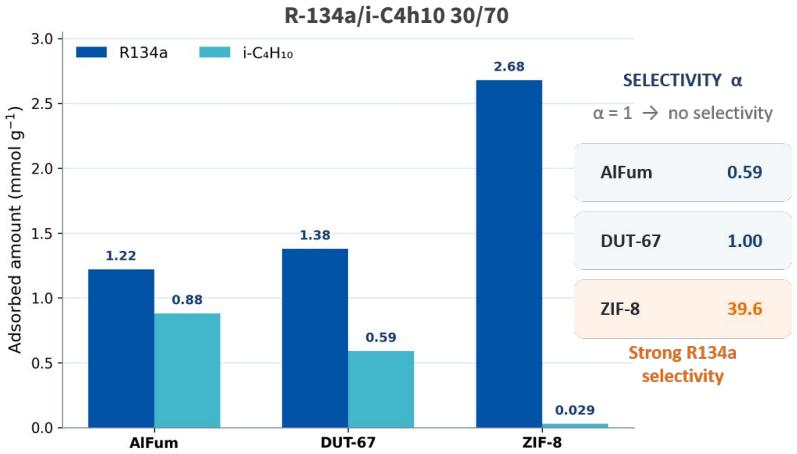
R-134a adsorption at low concentrations (100-5000 ppm)

- ZIF-4 provides the highest R134a uptake across the range. Al fumarate follows the same trend, while DUT-67 remains below 0.11 mmol g^{-1}.
- Thermal regeneration of MOF material required



R-134a adsorption at high concentrations (~70%)

- AlFum and DUT-67 show no useful R134a selectivity.
- ZIF-8 shows remarkable performance in i-C4H10/R-134a selectivity of α ≈ 40
- Thermal generation not needed: vacuum regeneration of MOF is sufficient



Alternative gases and chemical studies

Alternative gases for uRWELL

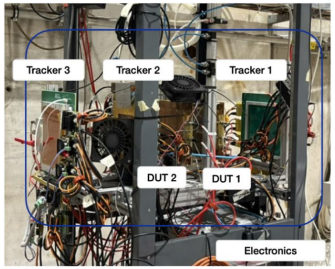
- Possibly a future detector, but so far tested only with CF4 mixtures for time resolution
- Ongoing tests with reduced CF4 and HFO as alternative to CF4

F and Cl production from HFOs

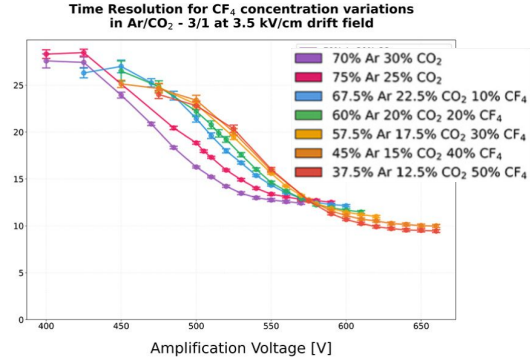
- Characterization of electrochemical cells to readout concentrations of pollutants at ppm level
- Characterization of Ion Selective Electrodes to readout Cl^- at ppm concentrations

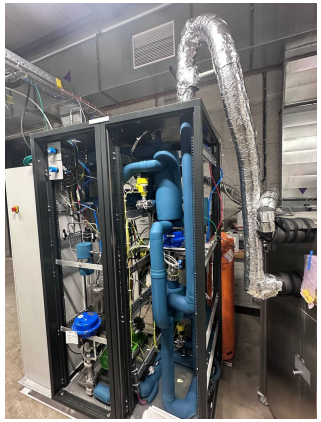
Commissioning of new gas recovery systems

- RICH1 C4F10 gas distillation system
- R-134a gas distillation system
  - Simulation and modeling for optimal operation parameters
  - Construction and commissioning of a new column-based distillation prototype



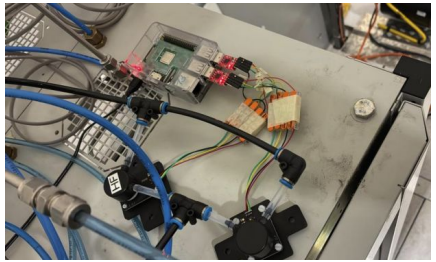
uRWELL @ DRD1 telescope





R-134a distillation prototype

HCl and HF cells setup



Conclusions

Several strategies to reduce GHG emissions from particle detectors

- Gaseous particle detectors contribute to a noticeable amount of CO2e emissions at CERN
- In the future the use of **F- gases** will likely be **more restrictive**

Gas recirculating systems

- First approach towards reducing GHG emissions
- Gas recirculation is advisable also for **small, laboratory-sized setups**

Gas recuperation systems

- Further approach to recirculation, advisable for **large systems** where some gas needs to be exhausted
- Complex and non-standard: each gas systems requires a **specific design** to recuperate the GHG gas component
- They require a considerable amount of **resources** and deep **expertise**
- Gas compression + centralized recovery plant under study

Gas separation, alternative gases and chemical studies

- Intense R&D on MOFs and membranes to adsorb F-gases from mixtures, enabling further recovery
- Studies on reducing and replacing **CF4** for uRWELL ongoing
- Chemical studies on pollutants production of **Cl-HFO** being carried out

Thank you

Backup

Not only detector performance: gas properties studies

Not only detector performance

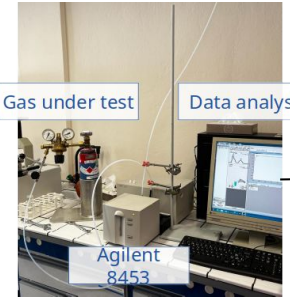
Understanding **physical** and **chemical** properties of gases is fundamental to detector operation

Environmental chemistry helps understanding pollutants formation

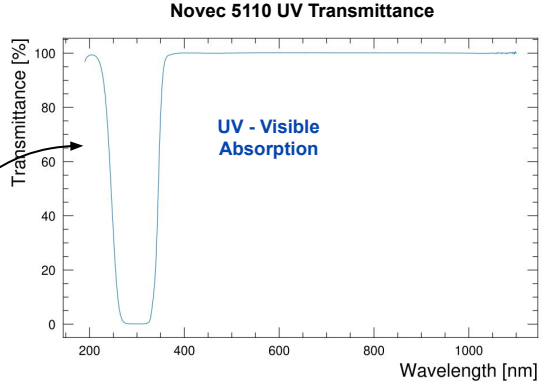
Gas molecules interaction in the atmosphere and in the detector

Rain out → Water solubility → critical for humidified gas mixtures
Oxidation → Reactivity with OH-
Photolysis → UV (wavelength < 300 nm) → quenching properties

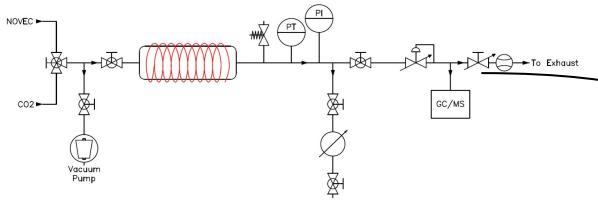
UV spectrometry

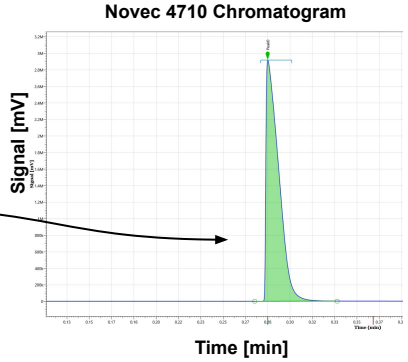


Thanks to B. Teissandier for helping in the measurements and providing the instrument

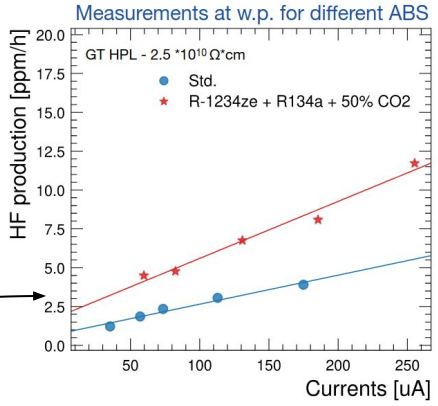


Novec 4710 water solubility setup schema









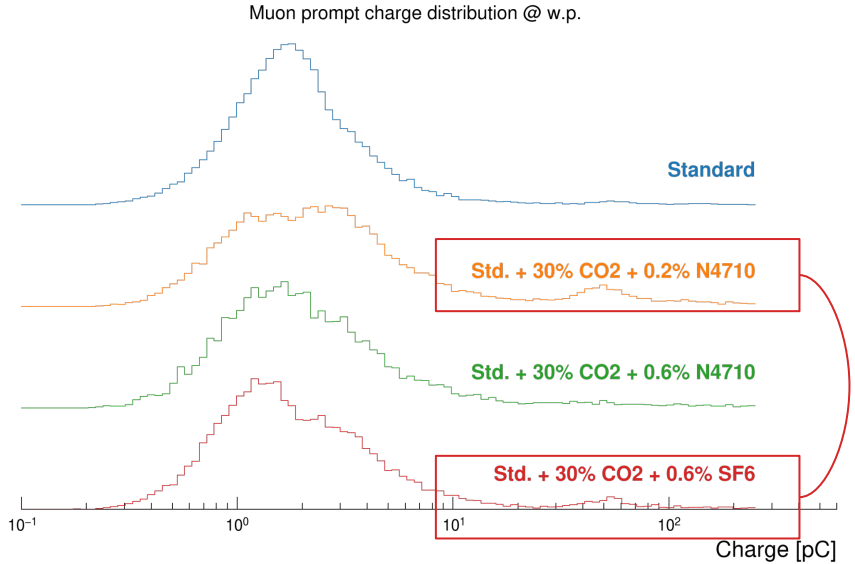
Novec 4710 with R-134a/CO2 gas mixtures

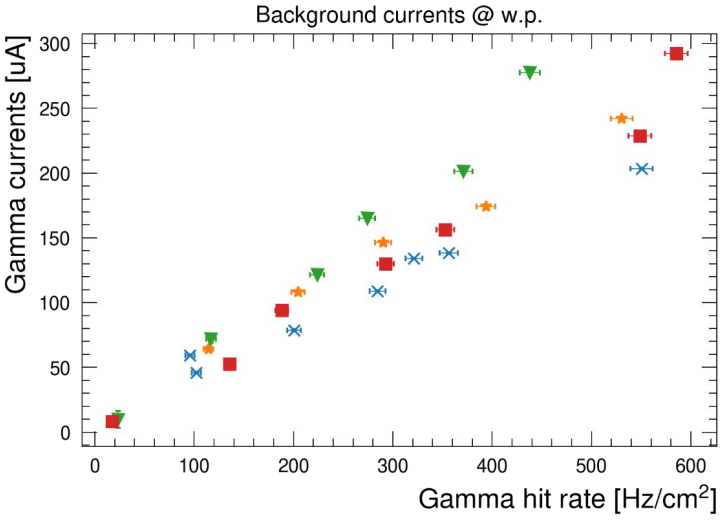
Novec 4710 + R-134a + 30% CO2 (+ 4.5% i-C4H10)

30% CO2 + 0.2% N4710 and **30% CO2 + 0.6% SF6** have similar performance (w.p., prompt charge, background currents)

30% CO2 + 0.2% N4710: lower gamma background currents

30% CO2 + 0.6% N4710: lower mean prompt charge but higher background currents → under investigation





R134A/IC4H10/SF6 95.2/4.5/0.3
R134A/CO2/IC4H10/NOVEC4710 65.3/30/4.5/0.2
R134A/CO2/IC4H10/NOVEC4710 64.9/30/4.5/0.6
R134A/CO2/IC4H10/SF6 64.9/30/4.5/0.6

Impurities studies: F- measurements

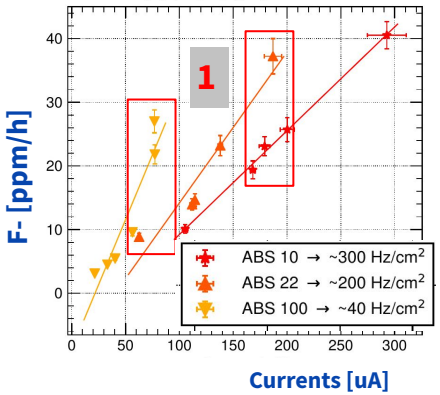
2019 ⇒ Std., HFO + R-134a + 40% CO2

1. F- production does **not** depend **only** on the **currents** but also on the gap **electric field**
2. Tested **R-1234ze** gas mixture produced **4x more F-** than std. gas mixture

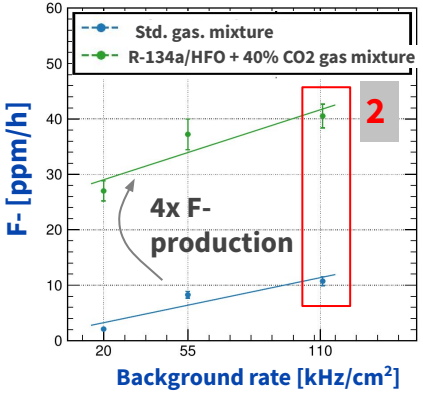
2022 ⇒ Std, Std + CO2 (+1% SF6), HFO + R134a + 50% CO2

3. 30% of CO2 in the standard gas mixture has the same F- production → **F- production** not **proportional** to R-134a
4. Using **1% SF6** to 30% CO2 + R-134a increases the **F- production** → under investigation
5. HFO + R134a + 50% CO2 produces **4x more F- than Std**

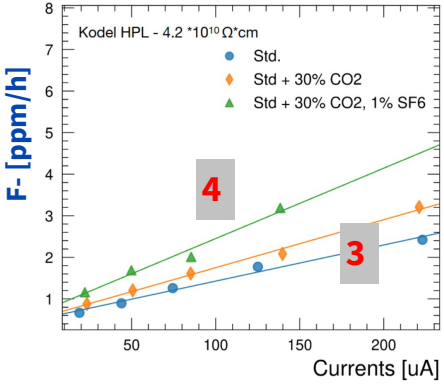
R-134a/HFO + 40% CO2



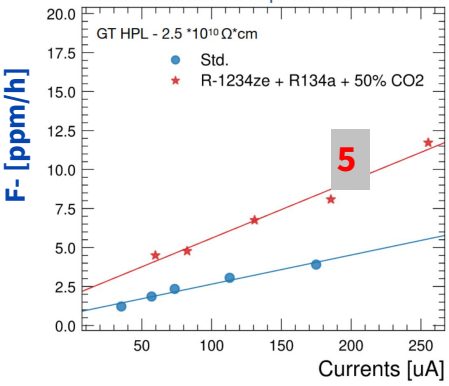
Rate @ w.p.



Measurements at w.p. for different ABS



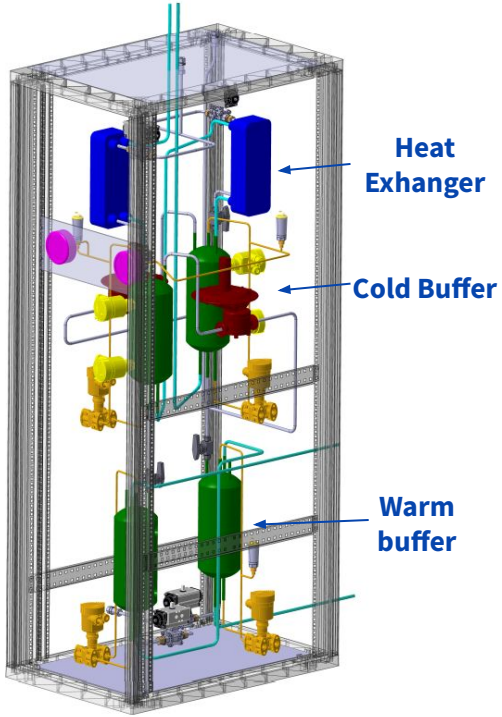
Measurements at w.p. for different ABS

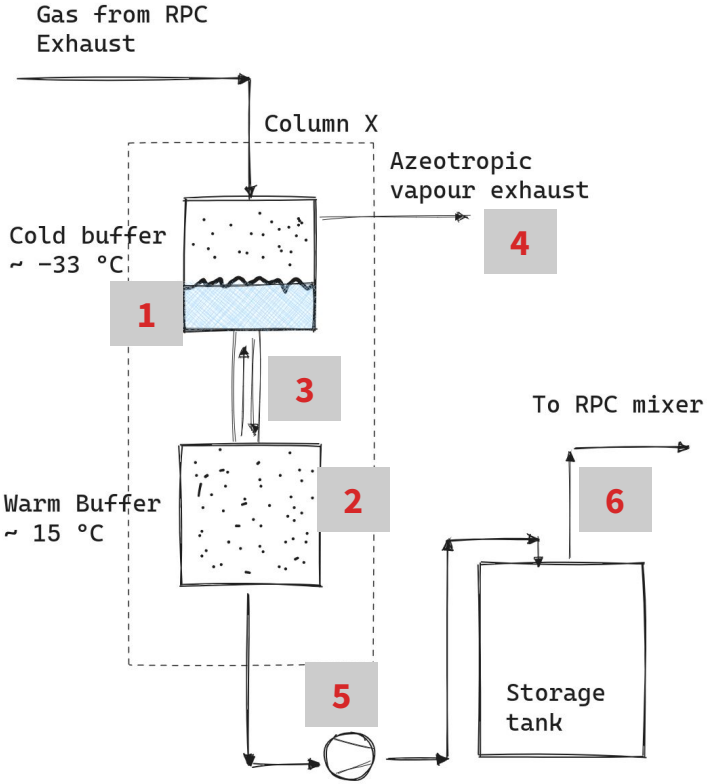


R-134a Recuperation system

Working design

1. **Gas mixture** completely cooled down **to liquid** in a “cold” buffer
2. **Liquid** mixture slowly heated up **to gas** into a “warm” buffer
3. Small thermodynamic **equilibrium** steps between **vapour** and **liquid**
4. **Azeotropic** vapour **exhausted** from cold buffer through a pressure controller
5. **R-134a liquid extracted** from cold buffer with a compressor
6. Compressor stores liquid in a tank ⇒ reused from CMS RPC mixer

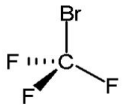




Evolution of F- gases in detectors

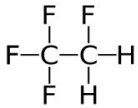
F- gases for particle detectors have always followed the industry and adapted to regulations

PFCs CFCs



R13B1

HFCs



R-134a

Ozone layer issue

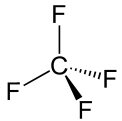
EU HFC regulation

2014

Montreal Protocol on HFCs

2019

Future?



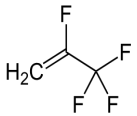
CF4

1987

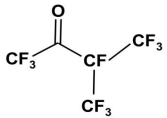
Montreal Protocol on CFCs

Global Warming becoming an issue

Eco-friendly HFOs, PFKs



R-1234ze



C5F10O

TFA, PFAS impact on health

HCl and HF cells setup

2023

EU PFAS Proposal

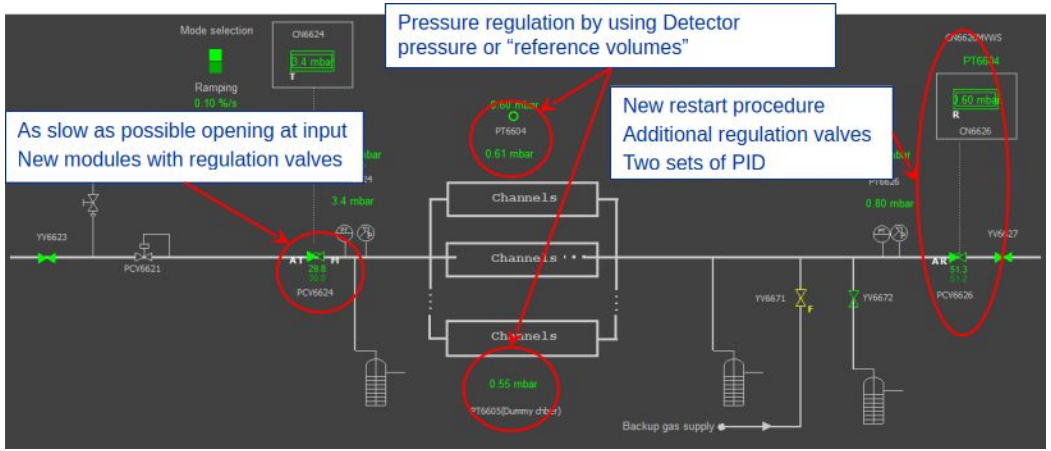
Gas recirculation optimization

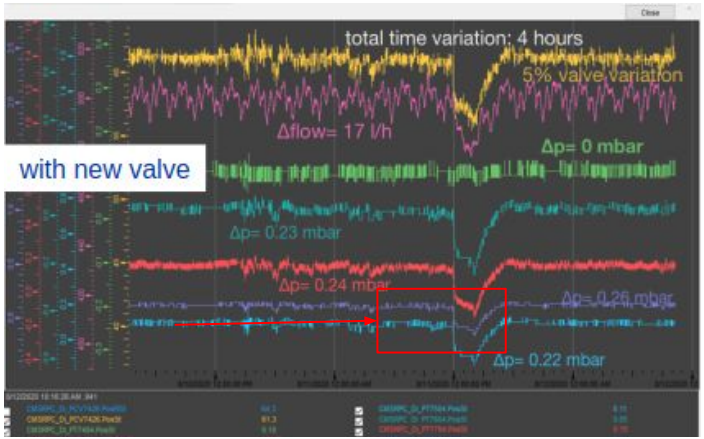
Minimize detector pressure/flow fluctuation

- Initial requirements ~ 1 mbar
- Current operation ~ 0.1 mbar

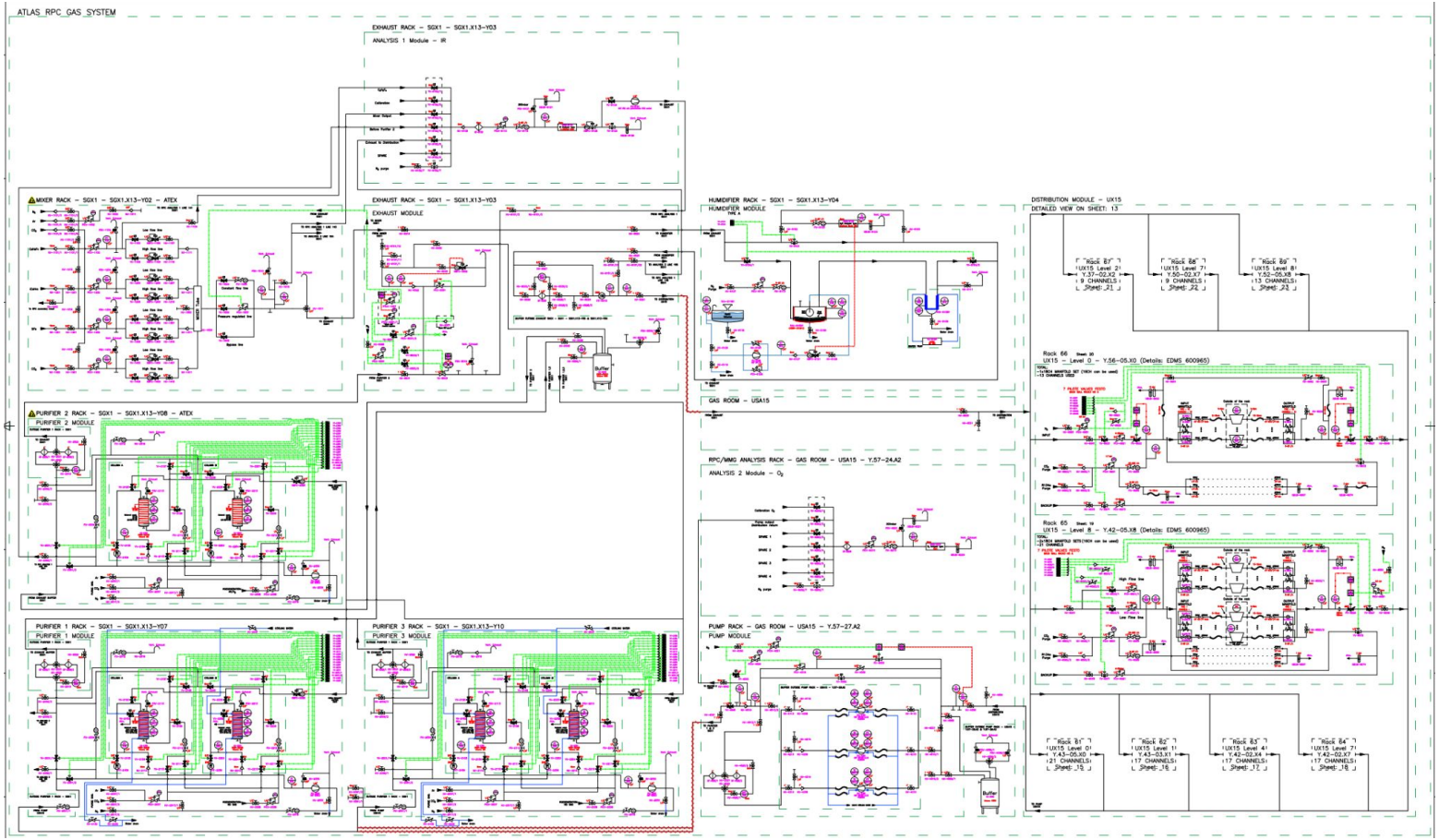
Upgrades of gas recirculation cannot be standardized

- Dedicated R&D
- Development of custom components/modules
- Qualification of new equipment





Modules of a large CERN LHC gas system (ATLAS RPC)



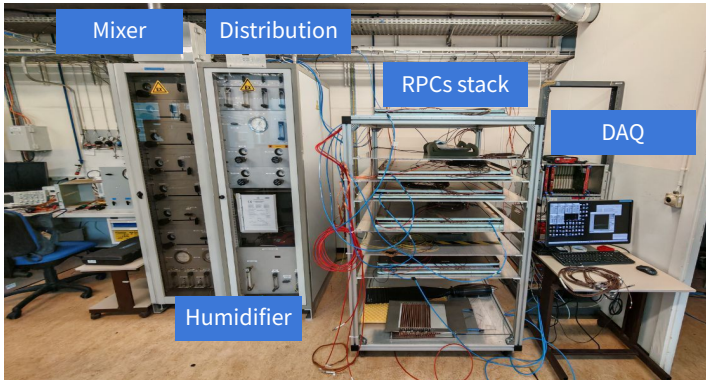
Study on alternative gases

Studies on detectors operated with eco-gas mixtures

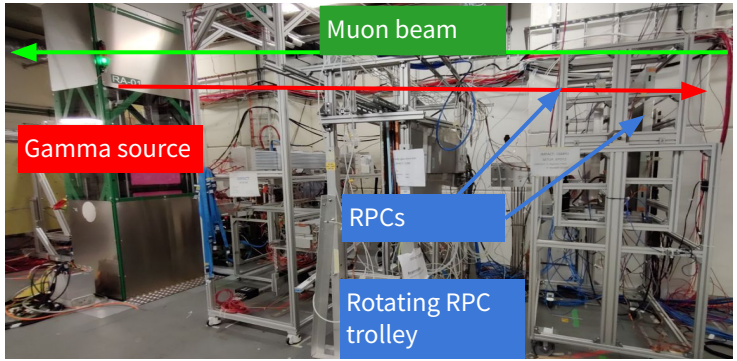
- **Laboratory** set-ups: HPL-RPC, glass RPC and uRWELLs
- **Facilities** set-up: HPL-RPC setup @ GIF++

Gas chemical properties studies

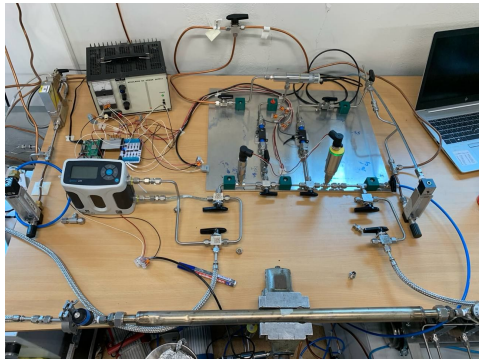
- Study on the **reaction** of new gases (e.g. Novec 4710) under controlled humidity and temperature conditions ⇒ eco-gases
- Study of the **gas absorption** properties of different materials ⇒ gas purification



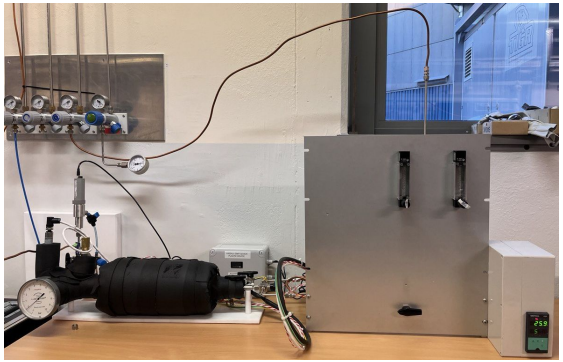
RPC setup @ lab 256



RPC setup @ GIF++

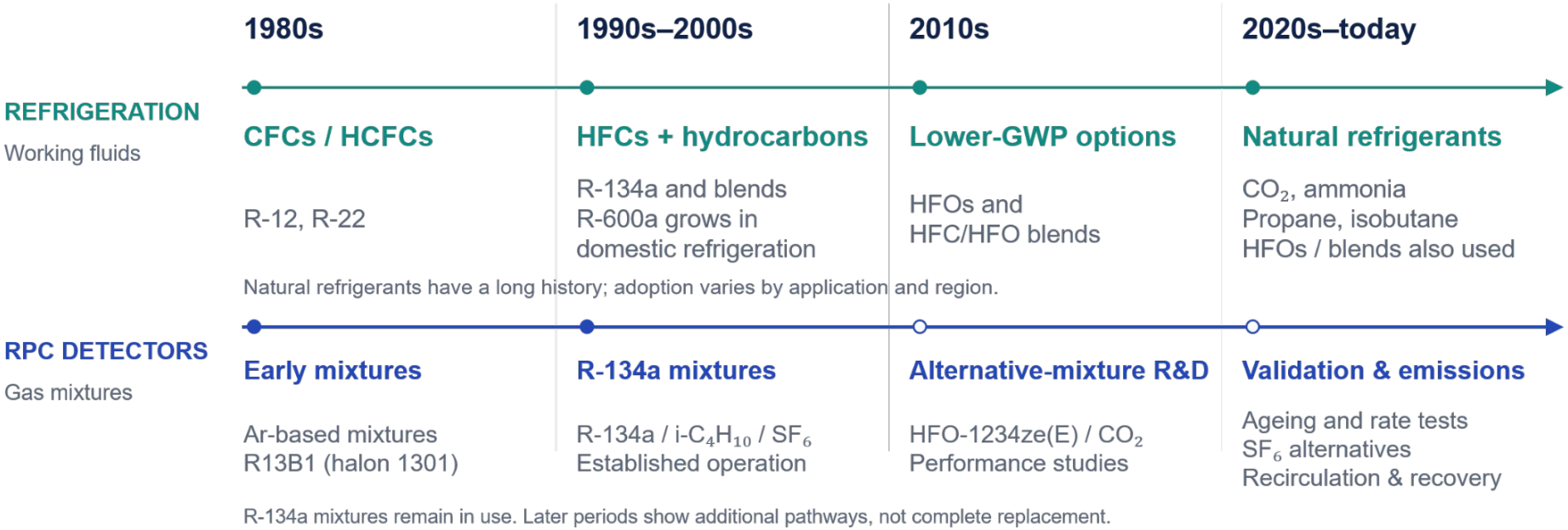


Cartridge regeneration setup



Novec 4710 hydrolysis setup

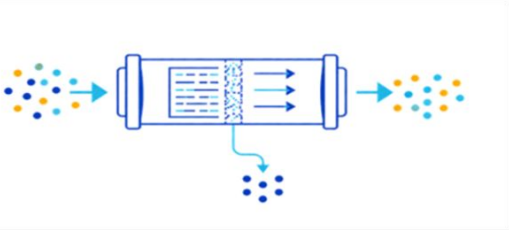
Evolution of F- gases in detectors



POLICY MILESTONES

1987	2014	2016 / 2019	2023	2024
Montreal Protocol CFCs and halons	EU F-gas Regulation HFC phase-down	Kigali Amendment Adopted / in force	Broad PFAS restriction Proposed; under review	New EU F-gas rules Steeper HFC phase-down

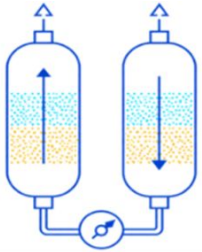
Gas recuperation techniques



Membrane separation

Selective permeation

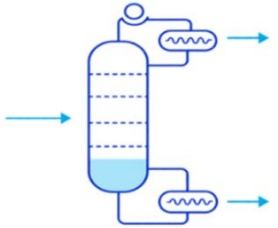
A selective barrier separates components according to permeability.



Pressure swing adsorption

Pressure-dependent adsorption

Adsorbent cycling captures and releases the target components.



Distillation

Different volatility

Components are separated through differences in volatility.

IN OPERATION

NEXT TARGET

CF_4 $C_2H_2F_4$ (R134a) C_4F_{10} SF_6